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Testing the GRB Variability/Peak Luminosity correlation using the pseudo-redshifts of a large sample of BATSE GRBs

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ABSTRACT
We test the correlation found by Reichart et al. (2001) between time variability and peak luminosity of Gamma-Ray Bursts (GRBs). Recently Guidorzi et al. (2005) found that this still holds for a sample of 32 GRBs with spectroscopic redshift, although with a larger scatter than that originally found by Reichart et al. (2001). However Guidorzi et al. (2005) also found that a power law does not provide a good description of that. We report on the same test performed on a sample of 551 BATSE GRBs with a significant measure of variability assuming the pseudo-redshifts derived by Band et al. (2004) (1186 GRBs) through the anticorrelation between spectral lag and peak luminosity. We still find a correlation between variability as defined by Reichart et al. (2001) and peak luminosity with higher significance. However, this subsample of BATSE GRBs show a higher scatter around the best-fitting power law than that found by Reichart et al. (2001) in the variability/peak luminosity space. This is in agreement with the result found by Guidorzi et al. (2005) on a sample of 32 GRBs with measured redshift. These results confirm that a power law does not provide a satisfactory description for all the GRBs, in contrast with the original findings by Reichart et al. (2001).

Key words: gamma-rays: bursts – methods: data analysis

1 INTRODUCTION

Years after the discovery of the first X-ray (Costa et al. 1997) and optical (Van Paradijs et al. 1997) afterglow counterparts to Gamma-Ray Bursts (GRBs) and the determination of the first redshift (Metzger et al. 1997), it has been possible to discover some correlations between burst-frame properties derived on a sample of some tens of GRBs with measured spectroscopic redshift. Some of them involve spectral and temporal properties: e.g., the anticorrelation between peak luminosity and spectral lag discovered by Norris et al. (2000), and the correlation between peak luminosity and temporal variability found by Fenimore & Ramirez-Ruiz (2000) and Reichart et al. (2001) (hereafter FRR00 and R01, respectively). Other correlations concern the spectrum and the energetics of the GRBs, like the Amati et al. (2002) correlation between the peak energy $E_{\rm p}$ of the burst-frame $E\,F(E)$ spectrum and the total isotropic-equivalent released energy, or the Ghirlanda et al. (2004) one between $E_{\rm p}$ and the collimation-corrected released energy for those GRBs for which it was possible to estimate the beaming angle. Similarly to the Amati relationship, Yonetoku et al. (2004) found that $E_{\rm p}$ also correlates with the peak luminosity L. Some of these relationships have been used to estimate the redshifts of large samples of GRBs. In particular, Band et al. (2004) (hereafter BNB04) used the anticorrelation between peak luminosity and spectral lag to estimate the redshift of 1186 BATSE GRBs.

Recently, the debate on the Amati and Ghirlanda correlations saw a couple of papers, Nakar & Piran (2005) and Band & Preece (2005), according to which at least a considerable fraction of the overall catalogue of BATSE GRBs cannot be consistent with those correlations. On the other side, three other papers suggest that the majority of the BATSE GRBs are consistent with the Amati and Ghirlanda correlations: Ghirlanda et al. (2005), Bosnjak et al. (2005) and Pizzichini et al. (2005). These authors, starting from different assumptions concerning the redshifts of the BATSE GRBs, independently show that the Amati and Ghirlanda correlations are confirmed. See the review by Amati (2005) for a detailed discussion of the debate.

Concerning the correlation originally found by R01 between variability and peak luminosity, also confirmed for X-Ray Flashes (XRFs; see Heise et al. (2001)) by Reichart et al. (2003), recently Guidorzi et al. (2005) (hereafter G05) have confirmed it through a larger sample of 32 GRBs with measured redshift, although with several differences from R01. In fact, they find a much larger scatter than that found by R01 with some notable outlier. Furthermore, G05 found that the power-law description originally obtained by Reichart et al. (2001) for a sample of 13 GRBs is no more satisfactory for an enlarged sample of 32 GRBs with measured redshift.

In this paper we test the variability vs. peak luminosity correlation similarly to G05, this time using a large sample of BATSE GRBs assuming the pseudo-redshifts derived from BNB04. In particular, we used a different approach from Ghirlanda et al. (2005): since BNB04 do not provide confidence intervals on both redshift z and peak luminosity L, following BNB04 we assumed the validity

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of the Norris et al. (2000) anticorrelation between peak luminosity and burst-frame spectral lag and for each BNB04 GRB we derived confidence intervals on both z and L and made sure that they were consistent with the BNB04 catalogue. Eventually we compared the results with those by G05.

The idea of using a large sample of BATSE GRBs with unknown redshift to test the variability/peak luminosity correlation is not new: Schaefer et al. (2001) used 112 BATSE GRBs to test the correlation between spectral lag and variability, as defined by FRR00, as both have been shown to be correlated with peak luminosity. The motivation of the investigation reported in this paper is based on several aspects. Firstly, it must be pointed out that Schaefer et al. (2001) made use of different definitions of both variability and peak luminosity, very similar to those given by FRR00. Although the two definitions of variability given by R01 and FRR00 appear to be correlated (see fig. 3 in FRR00), the relation between the two does not seem to be direct proportionality. In fact, Schaefer et al. (2001) found a best-fitting power-law index between L and V of $m_{\rm S01} = 2.5{\pm}1.0$ to be compared with that found by R01, $m_{\rm R01} = 3.3^{+1.1}_{-0.9}$. Secondly, nowadays the greater number of GRBs with known redshift than that available at that time, allowed to refine the best-fitting parameters of the lag/luminosity correlation (Norris 2002). For the first time, here we compare the properties in the variability/peak luminosity space of a sample of 32 GRBs with measured redshift studied by G05 with those of a large BATSE GRBs sample, using the definitions by R01 for variability and peak luminosity.

In Section 2 we discuss how we derived the samples of GRBs. In Section 3 we describe how we calculated the variability. In Section 4 we present our results and in Section 5 we discuss them.

2 THE GRB SAMPLE

From the catalogue published by BNB04 we first selected 1186 GRBs, for which all the information derived by BNB04 is available: redshift, spectral lag, best-fitting spectral parameters, peak luminosity. After requiring a significantly positive time lag, this sample shrank to 866 GRBs. Since BNB04 do not provide uncertainties on their measures of redshift and peak luminosity, we evaluated them as follows. We used the photon peak count rates (ph cm^{-2} s^{-1}) in the 50–300 keV band measured on a 256-ms time-scale, as reported in the BATSE catalogue [1]. In order to evaluate the energy peak flux (erg cm^{-2} s^{-1}) we need to know the spectrum. We adopted the same values as BNB04: i.e., we made use of the best-fitting spectral parameters found by Mallozzi et al. (1998) who fitted the energy spectrum of the peak with the Band function (Band et al. 1993). For those GRBs for which this piece of information was not available, like BNB04 we also assumed the average values found by Preece (2000) $\alpha = -0.8 \pm 0.1$ and $\beta = -2.3 \pm 0.1$, while $E_{\rm p} = E_0\,(2+\alpha)$ was taken from BNB04. From the photon peak flux we calculated the normalisation. We then evaluated the bolometric energy peak flux $F_{\rm B}$ in the 0–10^4 keV band and its uncertainty.

We calculated the best value and a 2-σ confidence interval for the redshift of each GRB assuming the validity of the anticorrelation between burst-frame spectral lag $\tau_{\rm B}$ and bolometric peak luminosity $L_{\rm B}$ originally found by Norris et al. (2000) and refined by Norris (2002): $L_{50} = 21.8\,(\tau_{\rm B}/0.35\,{\rm s})^{-1.15}$, $L_{\rm B} = L_{50} \times 10^{50}$ erg s^{-1}. We determined the range for the redshift z for which the point $(\tau_{\rm B}, L_{\rm B})$ was consistent within 2-σ with the Norris relation (see Fig. 1). We used the following: $\tau_{\rm B} = \tau_0/(1{+}z)^c$ (τ_0 is the spectral lag measured in the observer frame; $c = 0.6$, that accounts for both cosmological dilation and narrowing of pulses with higher energy found by Fenimore et al. (1995)) and $L_{\rm B} = 4\pi\,D_{\rm L}^2(z)\,F_{\rm B}$, where $D_{\rm L}(z)$ is the luminosity distance at redshift z. Here we adopted the same cosmology as BNB04: $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

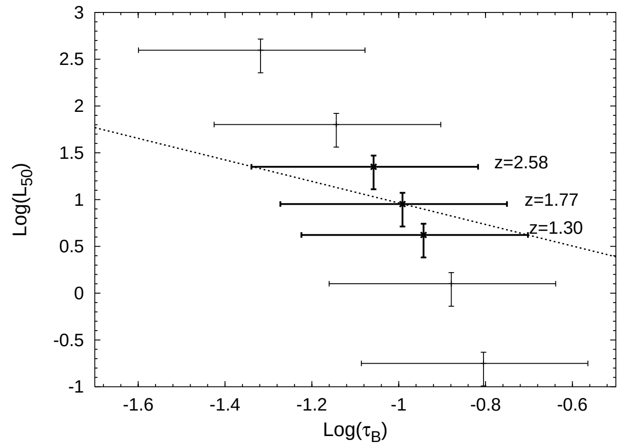

Figure 1. Example of how we determined the redshift confidence interval in the case of trigger # 228. Dashed line shows the Norris relation. Error bars are at 2-σ. The result for this GRB is $z = 1.77^{+0.81}_{-0.47}$. BNB04 found for this GRB $z = 1.435$.

We point out that the uncertainties on $\tau_{\rm B}$ and $L_{\rm B}$ have been propagated from those affecting the measures of the lag itself and of the energy peak flux, respectively (at each fixed z). We studied the scatter distribution of the 2-σ lower and upper limits with respect to the Norris power-law: it turned out that for the 67% of the entire sample these limits are scattered more than 0.26 around the best-fitting power law. Since Schaefer et al. (2001) found a scatter of 0.26 we conclude that at least a fraction of 67% have estimated luminosities that are consistent with the scatter intrinsic to the lag-luminosity relation.

This is different from the approach followed by Ghirlanda et al. (2005), who assigned each GRB peak luminosity an uncertainty derived from its scatter with respect to the Norris relation (see their eq. 5). Understandably, our confidence intervals for z are fully consistent with the values provided by BNB04 for the entire sample of 866 GRBs so far considered.

Like Ghirlanda et al. (2005), we excluded 38 GRBs with $E_{\rm p} \leqslant 40$ keV because close to the lower boundary of BATSE energy pass-band and therefore likely to be biased. In addition, one GRB was rejected for its undetermined redshift range, leaving us with a BNB04 final subset of 827 GRBs.

Eventually, in order to comply with R01 energy band and cosmology, making use of the same spectral parameters as above, we derived the best peak luminosity and its 2-σ confidence interval in the burst-frame 100–1000 keV energy band from the best value for z and its 2-σ confidence interval, assuming this time $H_0 = 65$ km s^{-1} Mpc^{-1} like R01 and G05. Let $\Phi(E)$ be the photon spectrum at peak (ph cm^{-2} s^{-1}); L in the burst-frame 100–1000 keV was then computed according to eq. 1.

$$L \;=\; 4\pi D_L^2(z)\,\int_{100/(1+z)}^{1000/(1+z)} E\Phi(E)\,dE \qquad (1)$$

[1] http://gammaray.msfc.nasa.gov/batse/grb/catalog/current/tables/flux_table.txt

This is formally the same as eq. 9 in R01 and eq. 8 in G05.

3 VARIABILITY ESTIMATION

Variability V was estimated using the public BATSE 64-ms concatenated light curves [2]. For each GRB we interpolated the background by fitting with polynomials of up to $4^{\rm th}$ degree as prescribed by the BATSE team [3]. This procedure was applied independently to each of the four energy channels: 25–55 keV, 55–110 keV, 110–320 keV, and $>$ 320 keV. Variability was computed for each GRB independently in each channel according to the definition by R01 (eqs. 4–8 therein). Following R01, we adopted a smoothing time-scale of T_f with $f = 0.45$: T_f is the shortest cumulative time interval in which a fraction f of the total fluence is collected. Hereafter V_f is the variability obtained adopting a time-scale of T_f. Uncertainties on V_f have been calculated combining the statistical uncertainty expressed by eq. 8 of R01 with that due to the error on redshift z.

Eventually, for each GRB we performed a χ^2 test and rejected all the GRBs showing significantly different variability measures between different energy channels. This requirement relies on the definition of V_f: as explained by R01, the definition of variability already accounts for the narrowing of pulses with energy (Fenimore et al. 1995) (pulses' width is proportional to $E^{-\alpha}$, $\alpha = 0.4$) and for the cosmological energy shift. For those GRBs showing consistent measures of $V_{f=0.45}$ in all channels we considered the weighted average.

4 RESULTS

The selection of the GRBs with a significant and consistent measure of variability reduced the sample from 827 to 551 BNB04 GRBs.

Figure 2 plots $V_{f=0.45}$ vs. L for the subset of 551 BNB04 GRBs. We also plot 31 GRBs with known redshift derived by G05 using data from GRBM/*BeppoSAX* (Feroci et al. 1997; Frontera et al. 1997), BATSE/*CGRO* (Paciesas et al. 1999), FREGATE/*HETE-II* (Atteia et al. 2003), *Ulysses* (Hurley et al. 1992), Konus/*WIND* (Aptekar et al. 1995) and BAT/*Swift* (Gehrels et al. 2004). From the sample of 32 GRBs studied by G05 we ignored the peculiar subluminous GRB 980425, not shown in Fig. 2 for scale compression reasons. The correlation between V and L is confirmed with higher significance due to the high number of GRBs: the linear correlation coefficient is 0.437 (P-value of 5×10^{-27}), the Spearman's coefficient is 0.449 (P-value of 10^{-28}) and the Kendall's coefficient is 0.302 (P-value of 2×10^{-26}).

If we try to fit the correlation with a power law (eq. 2), the result is unsatisfactory (χ^2/dof$= 4238/549$).

$$\log L_{50} \;=\; m\,\log\left(V_{f=0.45}\right) \;+\; q \tag{2}$$

Similarly to G05 we conclude that a power-law fit is inadequate to describe to correlation between L and $V_{f=0.45}$. Nevertheless, if one fits it with a power-law model, the best-fitting index turns out to be $m = 0.85\pm0.02$. This is in contrast with the value originally found by R01 for a sample of 13 GRBs with known redshift, $m_{\rm R01} = 3.3^{+1.1}_{-0.9}$, and consistent with that found by G05 for a sample of 32 GRBs with known redshift, $m_{\rm G05} = 1.30^{+0.84}_{-0.44}$. Thus we infer that the correlation between L and $V_{f=0.45}$ appears to be shallower than that found by R01 and this confirms what G05 found for the GRBs with known redshift.

Apparently these 551 BNB04 GRBs seem to locate differently from the 31 GRBs with measured redshift (Fig. 3). This is mildly suggested by the result of a K–S test, which gives $D = 0.328$ with a probability of 9×10^{-3} that the two groups belong to the same class. If we study the scatter distribution of the 551 BNB04 GRBs with respect to the best-fitting power-law found by G05 for the GRBs with known redshift, with $m_{\rm G05} = 1.30^{+0.84}_{-0.44}$ and $q_{\rm G05} = 3.36^{+0.89}_{-0.43}$, it comes out that the mean residual is -0.443 (in Fig. 3 this corresponds to the residuals of the black circular points with respect to the black solid line). Hence these GRBs are on average $10^{-0.443}\sim0.4$ times as luminous as the sample of 31 GRBs with measured redshift. The scatter of the 551 BNB04 GRBs is $\sigma = 0.7$ to be compared with that of the 31 GRBs with known redshift, which is 0.6. The two distributions are shown in Fig. 4: the black solid line shows the scatter distribution for the 551 BNB04 GRBs, while the red dashed line shows the case of the 31 GRBs with measured redshift.

The results of the best-fitting power law and the scatter for the two groups of GRBs (BNB04 and G05) are reported in Table 1.

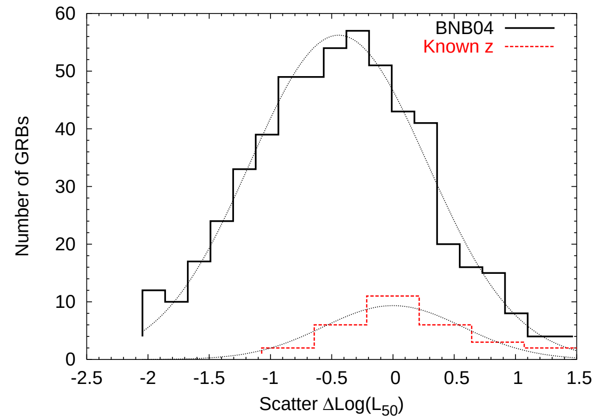

Figure 4. Distribution of the scatter of the two groups around the best-fitting power law obtained by G05: 551 BNB04 GRBs (black solid line) and 31 GRBs with measured redshift (red dashed line; the peculiar subluminous GRB 980425 is not considered here). Also shown are the two best-fitting normal distributions, whose σ's are 0.70 (BNB04) and 0.57 (G05).

Table 1. Best-fitting parameters for the two GRB sets for which we find significant correlation between variability and peak luminosity. m and q are the parameters of the best-fitting power-law: $L_{50} = 10^q\,V_{f=0.45}^m$. The last column reports the scatter around the best-fitting power law.

GRB Set	m	q	χ^2/dof	scatter
551 BNB04	0.85 ± 0.02	2.45 ± 0.03	4238/549	0.70
31 G05	$1.30^{+0.84}_{-0.44}$	$3.36^{+0.89}_{-0.43}$	1167/30	0.57

5 DISCUSSION

In agreement with the results by G05, the correlation between variability and burst-frame 100–1000 keV peak luminosity originally discovered by R01 is confirmed also using a sample of 551 BNB04 GRBs with a significant and consistent measure of variability, as

[2] ftp://cossc.gsfc.nasa.gov/compton/data/batse/ascii_data/64ms
[3] http://cossc.gsfc.nasa.gov/batse/batseburst/sixtyfour_ms/bat_files.revamp_join

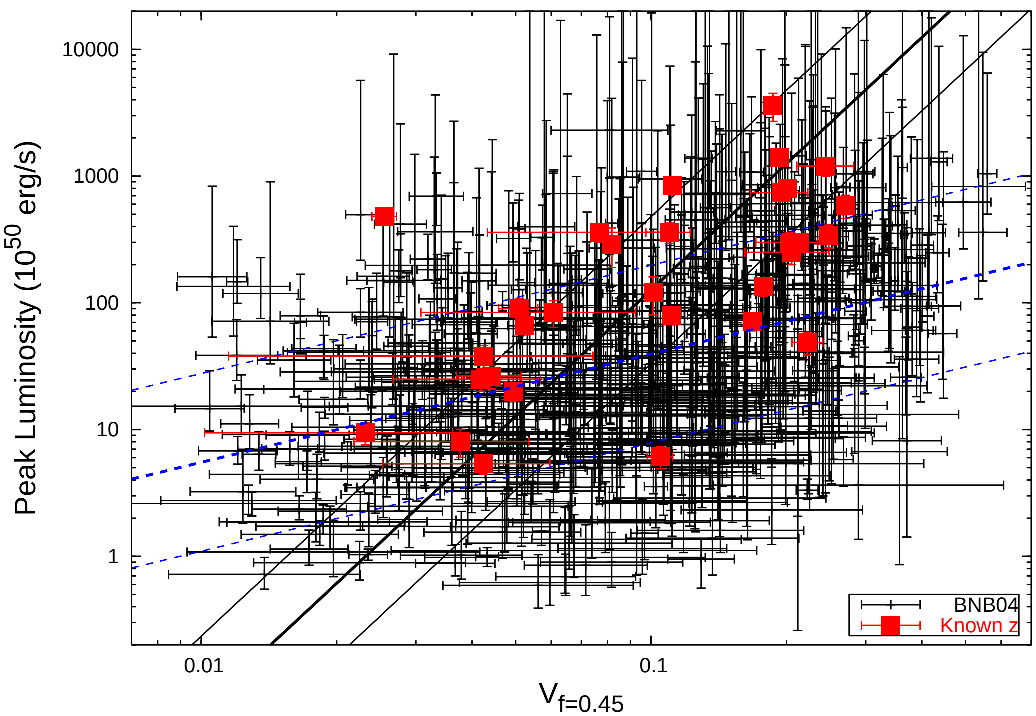

Figure 2. $V_{f=0.45}$ vs. Peak Luminosity for 551 BNB04 GRBs with significant variability. Black solid lines mark the best-fitting power law found by R01 (central line) and $\pm 1\sigma$ widths; blue dashed lines show the result that we found for 551 BNB04 GRBs. Red square points are GRBs with spectroscopic redshift taken from G05. For scale compression reasons the subluminous GRB 980425 is not shown.

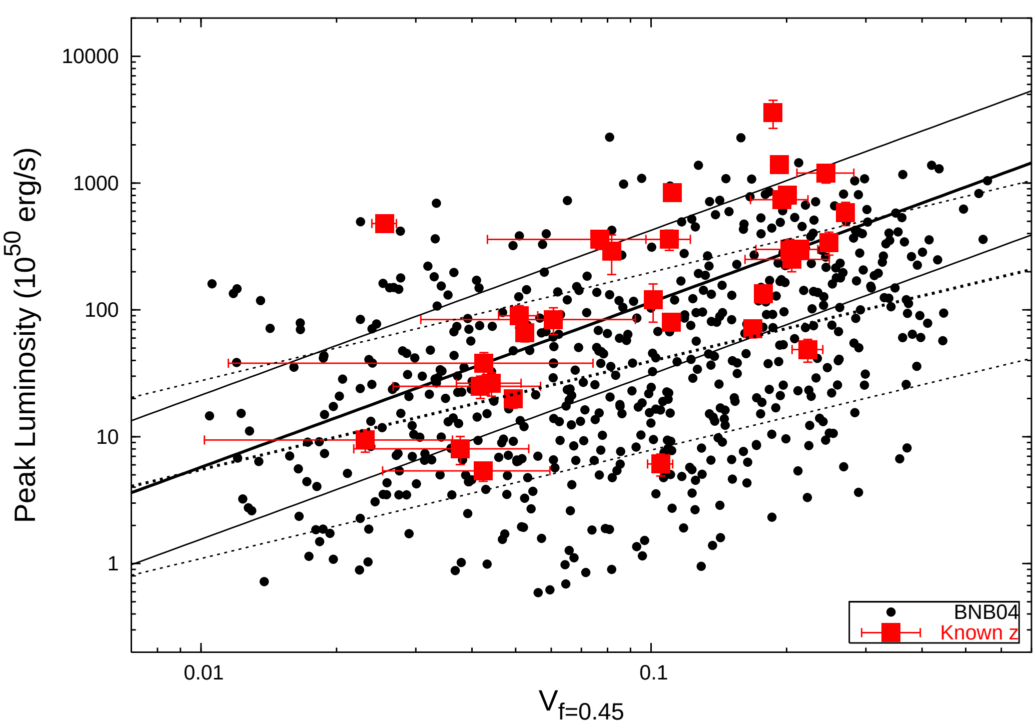

Figure 3. $V_{f=0.45}$ vs. Peak Luminosity for 551 BNB04 GRBs with significant variability. This Figure shows the same data as Fig. 2, aside from the error bars, here omitted for the sake of clarity. Black solid lines mark the best-fitting power law found by G05 (central line) and $\pm 1\sigma$ widths for a sample of 32 GRBs with known redshift (red square points). For scale compression reasons the subluminous GRB 980425 is not shown. Dashed lines show the result that we found for 551 BNB04 GRBs.

defined by R01. Like in the case of the GRBs with known redshift considered by G05, we find that the best-fitting power-law slope (index of $m = 0.85 \pm 0.02$) is shallower than that found by R01 ($m_{\rm R01} = 3.3^{+1.1}_{-0.9}$). However, like G05 we find that the power-law description of this correlation is inadequate (χ^2/dof of 4238/549). The result obtained for 551 GRBs with pseudo-redshift derived from the lag/peak luminosity relationship is in agreement with that found by G05 for a sample of 32 GRBs with spectroscopic redshift and is incompatible with the best-fitting power law obtained by R01.

The comparison between the sample of 551 BNB04 GRBs and that of the GRBs with measured redshift considered by G05 reveals that the former group is on average 0.4 times as luminous as the latter. Interestingly, despite the fact that a power law does not provide a good description of the correlation, the two groups show compatible power-law indices: 0.85 ± 0.02 (BNB04) vs. $1.30^{+0.84}_{-0.44}$ (G05).

We conclude that the disagreement found by G05 on a sample of 32 GRBs with known redshift with respect to the original results by R01 derived from a sample of 13 GRBs with known redshift is confirmed by the sample of 551 GRBs with pseudo-redshifts estimated from the spectral lag/peak luminosity anticorrelation.

A thorough discussion and possible explanations of the discrepancy between the results obtained by R01 and those by G05, consistent with those presented in this paper, is reported in G05. However, we remark that the results derived by R01 were based on a sample of only 13 GRBs with measured redshift available at the time, some of which have just limits on the peak luminosity. Remarkably, despite the fact that the sample of 32 GRBs with known redshift studied by G05 collects light curves from different spacecraft and the sample here considered of 551 BNB04 GRBs consists of BATSE data only, the results are consistent with each other.

The fact that the BNB04 GRBs are on average less luminous than the 31 GRBs with measured redshift could reflect the following possible observational bias: the more luminous GRBs are more likely to have measurable redshift at lower wavelengths.

In summary, the two samples of GRBs show the same properties in the variability/peak luminosity space: in either case the correlation is confirmed, although it turns out to be inconsistent with that found by R01. The only difference, aside from the lower average luminosity of the BNB04 sample already discussed, is a little higher scatter of the BNB04 GRBs around the best-fitting power-law: $\sigma = 0.7$ to be compared with $\sigma = 0.6$ of the 31 G05 GRBs.

It is also worth mentioning that, when we selected the 551 BNB04 GRBs out of a sample of 827 GRBs by requiring significant and consistent measures of variability across different energy channels for each single GRB, a considerable fraction of the 827 GRBs do not match these criteria. Thus, unlike the findings by R01, we find that there are GRBs whose variability as defined by R01 does depend on the energy channel.

These results are not necessarily in contradiction with those by Schaefer et al. (2001) derived from a sample of BATSE GRBs. First of all, because the definitions of variability and peak luminosity adopted by those authors are taken from FRR00. Regarding the definition of variability, from fig. 3 of FRR00 we can estimate a power-law relation between the two measures of variability according to the following: $V_{\rm FRR} \propto V_{\rm R01}^{\delta}$, with $\delta \sim 0.8 - 0.9$. The best-fitting power law found by Schaefer et al. (2001) between $L_{\rm FRR}$ (peak luminosity as defined by FRR00) and $V_{\rm FRR}$ has an index of $m_{\rm S01} = 2.5 \pm 1.0$. Then it is: $L_{\rm FRR} \propto V_{\rm R01}^{\delta\, m_{\rm S01}} \sim V_{\rm R01}^{2.1\pm0.9}$. It must be pointed out that the relation between the two definitions of variability should be investigated in detail, since the above approximation is based on fig. 3 of FRR00, based on 8 GRBs only. Nonetheless, this shows that the power-law index between variability and peak luminosity does depend on the definitions adopted. Moreover, the definition of variability given by FRR00 appears to be disputable in some points: e.g., the action of rebinning by a non-integer factor the light curves to report them to a fixed reference frame, dramatically affects the nature of Poisson counting statistics of the time series. Consequently, the variance that must be subtracted in the variability expression (eq. 2 in FRR00) is no more Poissonian and should be corrected accordingly. In general, the operation of splitting the counts integrated over a single time bin and use them to evaluate the variability is potentially risky, especially when the smoothing time-scale, proportional to the GRB duration, is relatively short.

6 CONCLUSIONS

We derived a selected sample of 551 BATSE GRBs from the BNB04 catalogue of GRBs assuming pseudo-redshifts based on the peak luminosity/spectral lag anticorrelation (Norris et al. 2000). The GRBs of this sample have been selected out of a sample of 827 BNB04 GRBs by requiring a significant and consistent measure of variability across the different energy channels, as defined by R01. Unlike R01, we find that not all of the 827 BNB04 GRBs we initially considered show a consistent measure of variability for different energy bands.

We confirm the correlation between variability and peak luminosity for the subsample of 551 BNB04 GRBs. In agreement with the results by G05 on a sample of 32 GRBs with measured redshift and in contrast with the original results by R01 on a sample of 13 GRBs with known redshift, we find that a power-law description of the correlation is inadequate. Nonetheless, if we try to fit it, we obtain a power law which is significantly shallower ($m = 0.85 \pm 0.02$) than that found by R01 ($m = 3.3^{+1.1}_{-0.9}$) and consistent with that found by G05 ($1.30^{+0.84}_{-0.44}$).

Finally, we note that the sample of 551 BNB04 GRBs are on average less luminous by a factor of ~ 0.4 with respect to the GRBs with measured redshift. We ascribe this difference to the fact that the sample of GRBs with measured redshift has been biased so far in favour of the more gamma-ray luminous GRBs, which on average had high fluences and then for which, consequently, more precise localisations were possible. This is probably true for the very first GRBs with measured redshift. We expect that *Swift* will clarify this issue as soon as it will discover a number of GRBs with low peak luminosity and measurable redshift.

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